4-3-2024

Investigating Drivers of High Wetland Loss Rates in Brackish Marshes of the Mississippi River Delta

Natalie M. Matherne

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INVESTIGATING DRIVERS OF HIGH WETLAND LOSS RATES IN BRACKISH MARSHES OF THE MISSISSIPPI RIVER DELTA

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in

The Department of Oceanography and Coastal Sciences

by

Natalie Matherne

B.S., Southeastern Louisiana University, 2021
May 2024
ACKNOWLEDGEMENTS

I would like to thank the members of the Quirk lab both past and present for their help on this project. I would also like to thank my family and friends for their support during this time. Also, a special thanks to my committee members-Tracy Quirk, Giulio Mariotti and John ‘Andy’ Nyman.
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ABSTRACT

Coastal wetlands provide numerous ecological services, but high rates of wetland loss have been seen, especially within the Mississippi River Delta. The erodibility of the marsh, which depends on its strength, can be affected by waterlogging-impacted factors. This study focused on investigating factors influencing soil shear strength in brackish to intermediate salinity marshes along the northern Gulf of Mexico coast using a comparative field study and a controlled greenhouse experiment to test the hypothesis that soil waterlogging reduces soil strength. I predict species-specific responses such that marshes dominated by the *Sporobolus pumilus* (formerly, *Spartina patens*), which is less flood tolerant and forms hummock-hollow microtopography, will have lower soil strength than marshes dominated by the more flood-tolerant *Sagittaria lancifolia*. The comparative field study tested differences in strength and stability between stable and unstable *Sporobolus* marshes spanning three locations and four sites (Chenier Plain and Barataria Bay, Louisiana and Grand Bay, Mississippi) and a stable *Sagittaria* marsh (Barataria Bay, LA). Hummock-hollow topography was evident in both the Chenier Plain and Barataria marshes. These hollows had significantly weaker shear strength than the hummocks. The stable marshes had 3.5 times greater soil shear strength on average when compared to the unstable marsh. *Sporobolus* and *Sagittaria* marshes in Barataria Bay had lower elevation and higher inundation depths than the two stable *Sporobolus* sites in the Chenier Plain and Grand Bay. The greenhouse study tested the effects of flooding (5, 45, and 90% time flooded) and nutrients (control and 2 mgN/L + 0.1 mgP/L) on growth and strength of *Sporobolus pumilus* and *Sagittaria lancifolia*. *Sporobolus* at higher elevation had higher aboveground biomass and higher shear strength than at low elevation. Overall, in both field and in a greenhouse setting, soil strength and biomass production of *Sporobolus* is negatively affected by highly flooded
conditions, while *Sagittaria* is able to remain consistent throughout various flooding regimes in terms of above and belowground biomass and shear strength at low salinity.
CHAPTER 1. FACTORS INFLUENCING SOIL SHEAR STRENGTH IN BRACKISH GULF COAST MARSHES: A COMPARATIVE FIELD STUDY

1.1. INTRODUCTION

Wetlands play an important role in the Earth’s biosphere by providing functions such as biogeochemical cycling, high rates of carbon accumulation, and habitat and food for organisms. Coastal salt marshes are some of the most productive ecosystems on Earth having rates of net primary productivity of up to 8000 g C m$^{-2}$ yr$^{-1}$ (Meaha et al. 2020). Wetlands also provide humanistic services including protection from storms, fostering fisheries through habitat and resource provisioning, and providing recreational opportunities. In total, the ecosystem services provided by tidal wetlands are valued at 10,000 USD per hectare (Barbier 2011).

Despite the value of wetlands, approximately 50% have been lost globally since the 1900s and by 2100, and 78% is predicted to be lost due to sea level rise (Spencer et al. 2016). Approximately 41% of coastal wetlands in the United States are in the Mississippi River delta (Coleman et al. 1998) where rates of loss have ranged from 28 to 84 km$^2$ per year since 2016 (Couvillion et al. 2017). With rates of eustatic sea level rise averaging 3.4 mm yr$^{-1}$ (NASA 2020) coupled with high subsidence rates, the Mississippi River delta region is currently facing one of the highest relative sea level rates in the world at 12 ± 8 mm per year (Jankowski 2017). The causes of wetland loss include relative sea level rise, subsidence, and anthropogenic impacts such as coastal development and oil and gas extraction activities (Spencer et al. 2016; Couvillion et al. 2011; Piazza and Peyre 2009). Though marsh loss in Louisiana has largely been attributed to subsidence, sea level rise and human development, lateral erosion of the edge is also an important mechanism of marsh loss (Leonardi et al. 2015, Wilson and Allison 2008).
Marsh edge erosion occurs continuously through normal wind and wave activity, and abruptly through storm events. Wind and wave erosion can result in marsh fragmentation and ponding resulting in permanent marsh loss over longer periods of time (Ortiz et al. 2017). Hurricanes can cause massive erosion over short time scales. In Louisiana and elsewhere, edge erosion is the predominant mechanism of marsh loss in open bays and is mainly caused by wind and wave energy. A positive correlation was found between the rates of marsh edge erosion and the average force of the impacting wind and wave energy computed through the wave model (Marani et al. 2011). The forces exerted by wave impact cause the removal of the sediment through a semi-continuous and steady process. Vegetation can lessen the impact of waves but cannot protect areas outside or below their root zone. Poor soil quality can lead to increased erosion from wind and waves, with waves being a major force causing erosion (Marani et al. 2011). This erosion process contributes significantly to the loss of marshes. One reason for this loss is the erosion occurring beneath the layer where plants’ roots grow, which is evident by the water and marsh interaction (Nyman et al. 1995). However, high erosion rates along some marsh coastlines are not caused by wave energy. In a former interdistributary bay of the Mississippi River delta, Barataria Bay, extremely high rates of edge erosion in the mid-bay occur in areas of little fetch and wind wave energy, suggesting that: (1) the marsh is inherently weak due to intrinsic properties (e.g., low live biomass, highly degraded organic matter; (Sasser et al. 2018, Foote et al. 1997) and (2) external drivers such as excessive inundation and high nutrient loads are weakening the soil (Bulseco et al. 2019, Bowen et al. 2020, Reed et al. 2020).

Marsh erodibility, or the intrinsic properties reducing soil strength, may vary depending on belowground plant biomass and soil properties and seems to vary among marsh types depending on the plant species and morphology. Living plant roots and rhizomes provide
physical structure and strength that help to hold the sediment together and increase the shear strength of the soil. Salt marsh soils with a higher abundance of roots and rhizomes tend to have greater shear strength (Turner 2011). Fresh marshes in the York River estuary, VA had lower shear strength than salt marshes. Fresh marshes were dominated by *Peltandra virginica* with a root system comprised of tubers with porous aerenchyma tissue. The salt marshes were dominated by *Sporobolus pumilus* (formerly *Spartina patens*), which has comparatively smaller rhizomes with a tightly interwoven root network that may hold the soil more effectively (Gillen et al. 2020). Soil properties such as the amount of organic matter may also influence soil strength and differ among marsh types. For example, brackish marshes in Barataria Bay, LA are two to three times more erodible than saline marshes associated with lower soil bulk density, higher soil organic matter content, and ultimately a lower soil shear strength in the root layer in brackish marshes (Valentine et al. 2021). Further, marshes with low live root biomass, high soil organic matter content, high porosity, and low bulk density can be more susceptible to erosion (Sapkota and White 2019).

External factors such as excessive inundation or high nutrient loads may play an important role in influencing belowground biomass and soil properties. Flooding is an important mechanism for sediment deposition and accretion (Cahoon and Reed 1995) but extended periods of inundation in marshes causes a reduction in the aboveground and belowground biomass, increases plant mortality and reduces soil volume (Tolley and Christian 1999, Snedden et al. 2015, Cahoon 2006). High nutrient loading has been shown to cause a decrease in below ground biomass in some marshes (Turner 2010, Valiela et al. 1976, Deegan et al. 2012) and increase decomposition (Bulseco et al. 2019), and thus may also play a role in reducing soil strength.
Here, we examine the role of flooding and marsh type on the soil shear strength of marsh along the northern Gulf Coast. Due to the high rates of erodibility (Valentine et al. 2021), brackish and intermediate marshes were the focus of this study. In August 2021, Hurricane Ida impacted the Louisiana coast as a category 4 storm, destroying an estimated 106 km$^2$, mostly in Barataria Basin (Couvillion 2021). Brackish marsh dominated by *Sporobolus pumilus* experienced a dramatic conversion to open water from Hurricane Ida, while adjacent marshes dominated by *Sagittaria lancifolia* and *Panicum hemitomon* experienced less of an impact (Figure 1). Satellite imagery shows that the majority of wetland loss occurred in the central north of Barataria Basin and that the impacts were heterogeneous across the dominant vegetation types. The spatial variation in hurricane impact across adjacent marshes differing in dominant vegetation prompted this investigation into the potential inherent characteristics of marsh vegetation and soil that makes some marshes more susceptible to erosion. While marshes dominated by *Sporobolus* are not likely inherently erodible, unexplained loss of *Sporobolus* has been documented in marshes in New England (Valiela et al. 2023, Watson et al. 2016). In the Great Sippewissett Marsh in Falmouth, Massachusetts, a rise in seal level has been linked to a decrease in the coverage of *Sporobolus*, which has been indirectly outcompeted by species such as *Distichlis spicata* (Valiela et al.2023). *Sporobolus* coverage has declined 30% in Coggeshall Marsh and 18% in Nag Marsh, Rhode Island from 2000 to 2014 (Watson et al.2016). The rate of relative sea-level rise in coastal Louisiana averages 12 ± 8 cm yr$^{-1}$ (Jankowski et al.2017), among the highest in the world. Many of the *Sporobolus* marshes in Barataria Basin are in an observed state of deterioration and are converting to mudflat.

Species inherent tolerances to flooding and growth strategy may play an important role in marsh morphology and ultimately soil strength. *Sporobolus* is a common marsh grass species
along the U.S. Atlantic and Gulf coasts found at mid-to-high elevations in salt marshes and in brackish marshes but has a wide ecological amplitude, also growing in low dune and beach habitats (Bertness 1991, Barkworth 2003, Leif 2013, Chabreck 1972). When compared to other more flood tolerant species, *Sporobolus* roots are less adapted at facilitates oxygen flow to roots under flooded conditions. (Gleason and Zieman 1981). In highly inundated conditions, *Sporobolus* exhibits a hummock/ hollow topography by having a phalanx growth pattern where it concentrates the root system under the shoots creating higher elevation mounds of dense roots called hummocks. In general, hollows are lower elevation areas that surround the hummocks (Windham 1999, Ye et al. 2006). Hummocks are usually formed in stressful environments (waterlogging and high salinity) and can be unstable with poorly developed roots connected to the underlying substratum (Stribling et al 2007). Thus, this microtopography can represent an intermediate stage in a degrading marsh that can eventually lead to ponding, more erodible soil and loss of marsh (Stribling et al. 2007).

*Sagittaria* is a flood tolerant forb found in lower intermediate salinity and freshwater marshes in the southeastern U.S., Central and northern South America, and the West Indies. Belowground, *Sagittaria* has large tubers with clustered roots that supports rapid lateral growth (Baldwin & Mendelssohn, 1998). Under optimum conditions of salinity and inundation, it is likely that both *Sagittaria* and *Sporobolus* generate strong soils within their rooting zones that would give rise to high shear strength. However, *Sagittaria* is more flood tolerant than *Sporobolus* and does not often form a hummock/hollow nature, as *Sagittaria* can benefit from some levels of inundation with rapid growth after a disturbance event (Baldwin & Mendelssohn, 1998). In a region of excessive flooding and low salinity, *Sagittaria* may produce a more erosion-resistant marsh than *Sporobolus* at marsh-scale.
The goal of this research is to test the hypothesis that flood-stressed *Sporobolus* marshes exhibit a hummock-hollow topography and are weaker and more susceptible to erosion than higher elevation *Sporobolus* marshes with a more homogeneous topography. Further, we predict that lower elevation marshes dominated by *Sagittaria*, which is more flood tolerant than *Sporobolus*, have greater soil strength than flood stressed *Sporobolus* marshes. We hypothesize that the integrity of the sediment in the lower elevation hollows of flood stressed *Sporobolus* marshes is weaker than the higher elevation hummock due to a lack of living root and rhizome biomass.
Figure 1. Marshes in Barataria Bay, Louisiana, before and after Hurricane Ida in December 2019 and April 2022. A *Sporobolus pumilus*-dominated marsh pre- (A) and post- (B) Hurricane Ida. A *Sagittaria lancifolia*-dominated marsh pre- (C) and post- (D) Hurricane Ida. Hurricane Ida land loss in Barataria (shown in red) (E). The majority of land loss occurred in areas dominated by floating *Sporobolus* (shown in orange) (Sasser et al. 1996) (F).
1.2. METHODS

1.2.1. Study sites

To test the hypothesis that waterlogging reduced soil shear strength depending on species-specific flood tolerance, we established a comparative field study in four locations along the Gulf of Mexico coast, including two in Barataria Bay, Louisiana (unstable *Sporobolus* (29°33′46.85″ N, 90°03′36.88″ W) and stable *S. lancifolia*-dominated marshes (29°40′10.84″ N, 90°07′44.07″ W), and two stable *Sporobolus* marshes, one in Grand Bay, Mississippi (30°19′25.68″ N, 88°28′07.30″) and the other in the Chenier Plain region in Sabine National Wildlife Refuge (29°52′45.22″ N, 93°28′15.84″ W), Cameron Parish, Louisiana (Figure 2).

The field locations differ with respect to proximity to the coast, geologic setting and hydrology and salinity. A stable *Sporobolus* marsh was located in Grand Bay, Mississippi. The Grand Bay National Estuarine Research Reserve is one of the largest undisturbed marsh-pine savannah habitats remaining in the Gulf coast and stands as one of the last remaining coastal marsh environments in Mississippi (Eleuterius 1974, Passeri et al. 2015). Over the past century, this estuary has experienced both natural and anthropogenic landscape changes. These include the diversion of the estuary’s sediment source and the erosion of its protective barrier island, known as Grand Batture. Consequently, Grand Bay’s marshes are eroding at a faster rate than any other marsh in the state of Mississippi (U.S. Geological Survey 2022, Passeri et al. 2015). The Grand Bay estuary is a marine influenced abandoned delta with no major freshwater input. This causes high salinity in this estuary (Eleuterius 1974). Grand Bay contained sandy soils at the site, with a majority of *Juncus* within the interior of the marsh. *Sporobolus* grew in patches near the exterior of the *Juncus* marshes. At higher elevation near the marsh, pine trees grew in the interior of certain areas.
A second stable *Sporobolus* marsh was located in the Chenier Plain region of Louisiana in Sabine National Wildlife Reserve. The Chenier Plain was formed from sediment deposition on the coastal boundary currents (Norman et al. 2022, Penland and Suter 1988). The Chenier plain consists of a wooded interior dominated by live oaks on ridges to tidal mudflats and fresh to saline marsh (Gould and McFarlan 1959, Penland and Suter 1988). The Chenier Plain in southwestern coastal Louisiana reach from Sabine Pass at the Texas/Louisiana border and extends nearly 200 kilometers eastward to Southwest Pass near Vermilion Bay. The mud deposits in the Chenier Plain are topped by marshland and within this landscape there are thin ridges composed of sand and shells, commonly referred to as cheniers (McBride et al. 2007, Russell and Howard 1935, Penland and Suter 1988). Land loss in the Chenier Plain is significantly lower than in the Deltaic Plain. This difference can be attributed to a slower subsidence rate in the Chenier Plain, which is associated with the thinner Holocene sediment layer in this region (Dunbar et al. 1999,). In the Chenier Plain one of the most severe land losses occurred within the area between 1956 and 1974, primarily concentrated in the marshes around Calcasieu Lake. The loss of approximately 197 square kilometers of wetlands in the Calcasieu Lake area during 1959-1974 and was caused by the widening and deepening of the Calcasieu ship channel in the mid-1940s, that was again widened in the mid-1960s. These changes have altered the hydrology and salinity in the region (Gosselink et al. 1979). In the future, the study area is projected to lose an additional 510 square kilometers of land over the next 50 years, representing 39% of the anticipated coastal land loss in the state (Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation and Restoration Authority 1998).
A *Sporobolus* marsh that has been subject to degradation and conversion to mudflat in Barataria Bay was selected as an unstable site and a slightly lower salinity marsh approximately 13.4 km north dominated by *Sagittaria* was selected as a stable marsh dominated by a more flood-tolerant species. Barataria Basin is an interdistributary basin of the Mississippi River located between the levees of the Mississippi River and the Bayou Lafourche distributary. The freshwater marshes to the north get most of their water from precipitation and the saltwater marshes to the south connect with the Gulf of Mexico (Day & Conner, 1987). The basin has been closed to river flow since 1930 and receives a small amount of water though the Intercoastal Canal. Barataria has lost nearly 5,700 acres of wetland between the years 1974 and 1990 and is expected to lose another fifth of wetlands by 2045 (CWPPRA 2017). Barataria Bay has been experiencing rapid erosion and subsidence over the long-term and was subject to devastating marsh loss during Hurricane Ida in August of 2021. In Barataria Basin, LA northernly winds push water out of the bay which causes lower water levels while southernly winds push water into the bay creating higher water levels. South-facing shores with higher water levels experience higher sediment deposits as the waves break over the marsh. North-facing shores have waves that undercut the soil below the root level. This differential flooding and wind and wave dynamics causes north-facing marshes to erode twice as fast as south-facing marshes (Valentine and Mariotti, 2019). Many of the freshwater and *Sporobolus* marshes in this interdistributary basin of the Mississippi River are floating. Floating marshes (also known as flotant) are typically free-floating marshes composed of thin or thick mats of vegetation. In freshwater marshes the vegetation is dominated by *Panicum hermitomon* and in brackish marshes *Sporobolus pumilus* is the dominant species (Sasser et al. 1996).
1.2.2. Experimental design

A continuous water level and conductivity recorder (Aqua TROLL 100) was placed in each marsh approximately 20 m from the marsh edge. The vented probe was placed inside a (9 x 130 cm) PVC well placed to 60 cm depth. Water level was recorded every 15 minutes. The probe was attached to a PVC pipe to maintain the sensors approximately 15 cm above the bottom of the well to limit the potential for mud accumulating on the well bottom to impact the sensors. The elevation of the marsh surface at each water level probe was collected using an RTK GPS (Leica Viva GS16 GNSS rover). The water probe in Grand Bay was deployed for 5 months (11/2022-
4/2023), the water probe in Sabine was deployed 6 months (2/2023-8/2023), water probe in the *Sagittaria* marsh was deployed for 5 months (9/2022-2/2023), and water probe in the *Sporobolus* marsh was deployed for 11 months (10/2022-9/2023). Water level data was also utilized from nearby Coastwide Reference Monitoring System (CRMS) sites. Marsh elevation relative to the mean water level was calculated between November 2022 to January 2023 (2 months) using water probe data. These two months were used to standardize mean water level data.

1.2.3. Measurements

At each study site, three 100 m long transects were established from the marsh edge to the marsh interior. High precision elevation and vegetation measurements were collected every 10 m and soil strength measurements were made every 20 m along each transect. Elevation was measured using an RTK GPS (Leica GS-16). Species percent cover was visually estimated within a 1-m² quadrat using a modified Daubenmire percent cover class (Daubenmire, 1956). Shear strength was measured at depths of 5, 15, 25, 35 and, 45 cm using a Humboldt H-4227 Vane along the transect. Due to the high variability, ten replicate shear strength measurements were collected at each distance along transects.

Above- and belowground biomass was collected at three randomly selected representative locations at least 10 m from the marsh edge and 10 m apart. Aboveground biomass was clipped to the surface within a 0.5 x 0.5 m quadrat above the site where the below ground biomass was collected. Following collection of aboveground material, belowground biomass was collected using PVC pipes (15.5 cm x 60 cm) with a beveled bottom edge. A mallet was then used to pound the pipe into the ground. At sites exhibiting hummock-hollow microtopography, three cores were collected at each hummock and hollow. Core barrels were
capped and secured for transportation to the lab. An RTK GPS elevation measurement was collected at each sampling location.

Aboveground biomass was taken back to the lab and sorted by species and live or dead. The aboveground clippings were dried and weighed at 60°C to a constant weight. Cores for belowground biomass were sectioned into 10 cm depth segments and rinsed over stacked sieves of 2.00 and 0.71 mm mesh size. The belowground biomass was sorted by live and dead organic matter and then dried at 60°C to a constant weight.

Elevation was calculated relative to mean water level (cm) and mean high water level (cm) using in-situ water level and/or CRMS-based water level data, which were referenced to NAVD88. To account for tidal range differences among sites, $Z^*$, a unitless measure of relative marsh elevation, was used. $Z^*$ was calculated using the equation:

$$Z^* = \frac{\text{Marsh elevation (relative to mean water level)}}{\text{Mean high water} - \text{Mean low water}}.$$

1.3. DATA ANALYSIS

Differences in elevation, above and belowground biomass, percent soil organic matter and soil shear strength among sites were tested using analysis of variance (ANOVA). All residuals were checked for normality and homoscedasticity assumptions of analysis of variance and transformed, if necessary. Log transformations were used for aboveground and belowground biomass and soil shear strength. A LOGIT transformation was used for vegetation cover data (Warton and Hui 2011). Differences among sites in live, dead, and total belowground biomass, soil organic matter, and shear strength were tested with depth as a continuous repeated measure. Differences in elevation and biomass between hummocks and hollows were tested using t-test.
The effects of hummock and hollows on shear strength were tested using ANOVA with depth as a continuous repeated variable. The model assumes a linear relationship between two variables, with shear strength as the dependent variable and mean water level as the independent variable. The Tukey Honestly Significant Difference test was used for post-hoc multiple comparison tests. All data was analyzed using JMP SAS pro-16.

1.4. RESULTS

1.4.1. Marsh elevation and hydrology

Marshes differed with respect to elevation and tidal hydrology. The tidal range was approximately 26 cm larger in Grand Bay, MS than in the Sagittaria marsh in Barataria, which had the lowest tidal range (Figure 3, Table 1). Mean water level (MWL) averaged 1.3 cm above the marsh surface in the Sporobolus marsh in Barataria, which was flooded an average of 52% of the time and – 1.3 to – 5.0 cm at the other sites which were flooded 31 – 39% of the time (Table 1).
Figure 3. Water level relative to the marsh surface in four marshes – a *Sagittaria* marsh (A) and an unstable *Sporobolus*-dominated marsh (B) in Barataria Basin and two stable *Sporobolus* marshes, one in the Chenier Plain- Sabine Wildlife Refuge, Louisiana (C) and the other in Grand Bay, Mississippi (D) from November 2022 – January 2023.
Table 1. Summary water level data for four study marshes averaged over three months from 11/2022 – 1/2023.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sagittaria Barataria</th>
<th>Sagittaria Barataria</th>
<th>Sabine</th>
<th>Grand Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWL (cm, relative to marsh surface)</td>
<td>-1.3</td>
<td>1.3</td>
<td>-2.5</td>
<td>-5.0</td>
</tr>
<tr>
<td>MHW (cm, relative to marsh surface)</td>
<td>1.0</td>
<td>10.9</td>
<td>1.5</td>
<td>14.2</td>
</tr>
<tr>
<td>MLW (cm, relative to marsh surface)</td>
<td>-3.0</td>
<td>-4.6</td>
<td>-7.2</td>
<td>-16.2</td>
</tr>
<tr>
<td>Tidal range (cm)</td>
<td>4.0</td>
<td>15.6</td>
<td>8.7</td>
<td>30.4</td>
</tr>
<tr>
<td>% time flooded</td>
<td>39</td>
<td>52</td>
<td>35</td>
<td>31</td>
</tr>
</tbody>
</table>

Elevation relative to the MWL was significantly different between sites ($F_{3,40} = 9.12, P < 0.0001$; Figure 4A). The Grand Bay site was more elevated than the other sites though highly variable along the distance transects (Figures 4 & 5). The *Sporobolus* site in Barataria had the lowest elevation relative to mean high water (MHW) at -11 cm owing to a relatively high MHW level ($F_{3,40} = 5.46, P < 0.003$). Thus, relative to MHW, the degrading *Sporobolus* site was 16-18 cm lower than the other three sites. Accounting for differences in tidal range, $z^*$ also differed among sites with the *Sagittaria* site higher than the Grand Bay site ($F_{3,40} = 3.16, P = 0.0347$, Figure 3C).

Marsh elevation ($z^*$) differed among sites with distance from the marsh edge (Site x Distance: $F_{3,58} = 3.25, P = 0.0279$; Figure 5). Most notable was the decline in elevation with distance in the *Sagittaria* site and also in the interior of the unstable *Sporobolus* sites as compared to the other marshes. A hummock-hollow microtopography was present in both the unstable *Sporobolus* marsh in Barataria Bay and the stable *Sporobolus* marsh in Sabine, though lower in elevation and more prevalent in the Barataria Bay marsh (Figure 6). Hummocks in both marshes averaged 2.2 cm ± 0.2 higher than hollows ($P < 0.0001$).
Figure 4. Marsh surface elevation relative to mean water level (A), Marsh surface elevation relative to mean high water (B), and $Z^*$ standardized tidal elevation (C). Sites include a *Sagittaria* marsh, an unstable *Sporobolus*-dominated marsh in Barataria Basin and two stable *Sporobolus* marshes, one in the Chenier Plain- Sabine Wildlife Refuge, Louisiana and the other in Grand Bay, Mississippi ($n = 30$).
Figure 5. Standardized $Z^*$ for marsh elevation across distance (m). Four sites include a *Sagittaria* marsh (A), an unstable *Sporobolus*-dominated marsh (B) in Barataria Basin, a stable *Sporobolus* marsh in the Chenier Plain- Sabine Wildlife Refuge, Louisiana (C) and a stable *Sporobolus* marsh in Grand Bay, Mississippi (D). Values are means ± standard error ($n = 30$).
1.4.2. Species composition and cover

Total vegetation cover was similar among marshes and distances from the marsh edge (Figure 7). The percent cover of *Sporobolus* was 69% in Sabine, 32% in Barataria Bay, and 13% in Grand Bay marshes ($F_{2,34} = 15.87$, $P < 0.0001$). The *Sagittaria* site had 13% cover of *Sagittaria* and found at 15% of sampling plots, 32% cover of the vine *Vigna luteola*, 13% cover of *Panicum repens* and 21% cover of *Sporobolus*. Grand Bay had patches of *Sporobolus* (9% coverage overall and found at 6% of sampling sites) near the marsh edge but was dominated by *Juncus roemerianus* (37% coverage overall and found at 63% of sampling sites) in the interior.
Sabine had the highest percent coverage of *Sporobolus* with every distance (100% of sampling sites) having at least 40% coverage. The degrading *Sporobolus* marsh in Barataria had greater species richness than the stable Sabine site (Figure 7 B and C). Species such as *Panicum repens*, *Solidago sempervirens* and *Ipomoea pre-caprae* were all found within the degrading *Sporobolus* marsh.

![Figure 7](image-url)

**Figure 7.** Plant species percent cover in *Sagittaria*-dominated (Barataria) (A) and *Sporobolus*-dominated marshes (Barataria (B), Sabine(C), and Grand Bay(D)). Values are means (n=3).

1.4.3. Belowground biomass

Live and dead (total) belowground biomass was similar among marshes (Figure 8). Live biomass differed among sites depending on depth (Site x Depth: $F_{3,34} = 3.89$, $P = 0.0173$). The *Sporobolus* marshes tended to have greater live biomass just below the surface than the *Sagittaria* marsh with the exception of the hollows, which had very low live biomass throughout.
the depth profile. Live biomass was significantly greater in the hummocks than the hollows ($t = 5.67$, $P = 0.0299$), while dead biomass was significantly greater in the hollows than in the hummocks ($t = 13.51$, $P < 0.0017$; Figure 8).

![Figure 8](image)

**Figure 8.** Belowground biomass in four marshes – an unstable Sporobolus-dominated marsh separated by hummock (A) and hollow (B) samples and a Sagittaria marsh in Barataria Basin (C), and two stable Sporobolus marshes, one in the Chenier Plain- Sabine Wildlife Refuge, Louisiana (D) and the other in Grand Bay, Mississippi (E). Biomass samples in hummock and hollow areas were collected in the unstable Sporobolus site. Total live and dead biomass values are listed in g m$^{-2}$ ± standard error. Values are means ± standard error ($n = 3$).

1.4.4. **Soil shear strength**

Shear strength differed among marshes depending on distance from the edge and depth (Site x Distance x Depth: $F_{75, 2423} = 2.7$, $P < 0.0001$; Figure 9). Soil shear strength in both
Sagittaria and Sporobolus Barataria Bay marshes was low and uniform with depth and distance from the edge (Figure 9). There was greater variability in soil strength at the Sabine and Grand Bay sites with distance, which tended to increase with depth, likely due to a mineral-based substrate.

Shear strength differed between hummock and hollows with depth in the Barataria Bay Sporobolus site (Hummock/Hollow x Depth: P < 0.0007; Figure 11). The shear strength of hummocks was higher (7.6 kPa) closer to the surface in the live root zone than at lower depths (30-50 cm; 3.7 kPa). The hummocks in the current study had a mean shear strength of 5 kPa and the hollows had a mean shear strength of 0.4 kPa. Focusing on the live root zone, a significant difference in shear strength was also shown between sites and depth (Site: F$_{3,64} = 11.21$, P < 0.0001; Figure 10).
Figure 9. Soil shear strength in four marshes – a *Sagittaria* marsh in Barataria Basin (A), an unstable *Sporobolus*-dominated marsh (B), and two stable *Sporobolus* marshes, one in the Chenier Plain–Sabine Wildlife Refuge, Louisiana (C) and the other in Grand Bay, Mississippi (D). Five replicates were taken at five depths at distances of 0, 20, 40, 60, 80, and 100 m from the marsh edge. Values are means ± standard error (n=3).
Figure 10. Root zone soil shear strength in four marshes – a unstable *Sporobolus*-dominated marsh and a *Sagittaria* marsh in Barataria Basin, and two stable *Sporobolus* marshes, one in Sabine Wildlife Refuge, Louisiana and in Grand Bay, Mississippi. Depth is between 0 and 20 cm for the full rooting layer. Values are means ± standard error (n=3).
1.4.5. Factors influencing soil shear strength

Soil strength within the root zone was weakly, positively related to marsh elevation relative to MWL across sites ($R^2 = 0.07$ $P = 0.0355$; Figure 12). Lower elevation areas tended to have lower shear strength. The $Z^*$ values show did not show an interaction between standardized tidal elevation and root zone shear strength.

Neither the live nor the dead biomass had a significant correlation with shear strength. These results may be limited due to the small sample size.

Figure 11. Soil shear strength in hummock/hollow topography at unstable *Sporobolus*-dominated marsh Barataria Basin, and a stable *Sporobolus* marsh in Sabine Wildlife Refuge, five replicates were taken at five depths. Values are means ± standard error (n=3).
Figure 12. The relationship between shear strength and elevation relative to mean water level relative to MWL across four study marshes. Sites include a stable *Sagittaria* marsh in Barataria, an unstable *Sporobolus* marsh in Barataria, a stable *Sporobolus* marsh in Sabine and a stable *Sporobolus* marsh in Grand Bay.
1.5. DISCUSSION

Brackish marshes are vulnerable to increased flooding from sea-level rise (DeLaune et al 1993), which may increase susceptibility to flooding stress. Here, we show that soil shear strength was lower overall in marshes that experience more flooding (e.g., Sporobolus in Barataria), but factors such as microtopography and substrate type (i.e., organic vs. mineral) also seem to play an important role. Belowground biomass did not have an impact on shear strength, but this effect may be attributed to the lower biomass observed at depths of 30-50 cm, where notably high shear strengths were found due to high mineral soil—particularly at the Sabine and Grand Bay sites.

Soil shear strength of the live root zone was lowest in the unstable Sporobolus marsh, which averaged 10 cm below MHW and was characterized by extensive hummock-hollow topography. Hollows lack significant live root biomass and have very low soil strength. In contrast, the Sabine and Grand Bay sites, which were on average 0.7 cm below and 10 cm above the MHW level respectively, had higher average shear strengths of 10.7 kPa and 15.1 kPa. Previous research has shown that tensile root strength of Sporobolus decreased after exposure to flooding, with a total of 39% loss in strength (Hollis et al 2021). Highly flooded conditions can lead to a decrease in the oxygen supply and subsequently less energy production in Sporobolus, which has smaller diameter rhizomes and less aerenchyma tissue than more flood-tolerant plant species (Naidoo et al 1992). Sporobolus in marshes organs located in Breton sound, La had greater belowground biomass production at higher elevations (Snedden et al. 2015). At lower elevation, Sporobolus experienced a 90% reduction in belowground biomass production (Snedden et al. 2015). This could of lead to weaker soil shear strength as a reduction in biomass and an increase in moisture content can lead to weaker soils (Tengbeh 1993). In contrast,
*Sagittaria* has adaptations to tolerate higher levels if inundation well-developed aerenchyma tissue that facilitates oxygen transport (Marburger 1993).

Soil strength of the marsh edge may differ from the marsh interior due to differences in soil bulk density, live root biomass, and waterlogging. Sediment deposition along the marsh edge can increase soil bulk density while greater water drainage can enhance conditions for root and rhizome growth compared to the marsh interior (Duvall et al. 2019). On the other hand, the marsh edge may have less biomass and more exposure to wave energy, which can weaken the soil (Gillian 2020). Additionally, an increase in inorganic sediment deposition and resuspension results in looser, mineral-rich soil, which can lower soil cohesion and shear strength (Gillen et al. 2021, Ameen et al. 2017). Shear strength was low and uniform across distances from the marsh edge in both the Barataria marshes. Across the Grand Bay and Sabine *Sporobolus* marshes, there was much greater variability in shear strength though without a clear gradient with distance indicating spatial variability that may be due to variability in root density and morphology and layers of mineral sediment.

Several studies have shown that soil strength is positively related to belowground biomass (Sasser et al. 2017, Snedden et al. 2015, Tengbeh 1993). This is most seen in the root zone that is able to create a network of roots and rhizomes that significantly enhances the soil’s shear strength (De Battisti et al., 2019; Tengbeh, 1993). However, we detected little impact of biomass on shear strength but his could be due to low biomass sample size. In the stable Sabine marsh, the amount of living biomass was significantly higher—by 321 g/m$^3$—than in the deteriorating *Sporobolus* site. Grand Bay, on the other hand, had the highest amount of dead biomass at 2,213 g/m$^3$, and had a shear strength 3.7 times higher than the unstable *Sporobolus* site indicating other factors impact marsh strength.
Soil shear strength in the live root zone differed among sites, but an even more pronounced difference occurred at depths below the live root zone that can be attributable to mineral sediment. Though not quantified in this study, I observed very different underlying substrates. Barataria Bay marshes were highly organic, while the Sabine marshes have a relatively high grand content (Bernier et al. 2011). Similarly, Grand Bay marshes have a high mineral content with a large sand component (Ellis 2022). Sediment composition was found to be the prominent factor in shear strength in salt marshes in Virginia over vegetation and salinity (Gillen et al. 2021). Mineral sediment increases soil bulk density (Gosselink et al. 1984) and an increase in mineral strength has been shown to increase soil strength (Gillen et al. 2020.). Grand Bay and Sabine both had a dramatic increase in shear strength below the root zone, which can be attributed primarily to higher bulk density soils. Sand particles are coarser and provide higher interlocking stability and clay particles have high surface areas to form strong frictional bonds (Valentine 2019). The root zone also contributes to the organic matter content and bulk density of the soil, which can influence the shear strength in different ways. The most significant factor influencing the variation in marsh soil strength across different vegetation types was identified as the live belowground biomass (Sasser et al. 2017). The composition of soil organic matter includes a complex network of roots that help to prevent erosion from mineral sediment. (Nyman et al. 1993, McCaffrey and Thomason 1980). Overall, higher density marsh soil can contain a high amount of organic matter but typically, bulk density declines exponentially as the percentage of organic matter increases (Morris et al. 2016) leading to possible weaker shear strengths.

Hummock-hollow topography is a prominent feature of wetlands and has been noted in tidal swamps and marshes in both fresh, brackish, and saline sites. (Courtwright and Findlay
In the hummocks, the depth profiles show that the majority of the shear strength for hummocks is in the top 20 cm. The top 20 cm is where the *Sporobolus* plant concentrated most of its live belowground biomass and where it experienced a phalanx growth (Windham 1999, Ye et al. 2006). The hummock-hollow topography was a common feature in both stable and unstable *Sporobolus* marshes. However, the unstable Barataria marsh exhibited a higher prevalence of counted hummocks and hollows compared to the stable Sabine marsh. The hummocks within these marshes were above the mean water level in terms of elevation in both *Sporobolus* marshes. The microtopography in the Sabine site were higher in terms of elevation within both the hummocks and hollows (z-values: 4.4 and 2.7). In contrast, the Barataria site exhibits lower elevations for both hummocks and hollows (z-value: 1.8 and .83). This could be due to the hummocks in Sabine being under less flooding stress than the Barataria hummocks. Shear strength was also much lower in the hollows compared to the hummocks (5.3 kPa vs .46 kPa). These hummocks lead to better oxidized environments due to improved elevation (Stribling et al. 2007). The growth pattern of *Sporobolus* contributes to the formation of microtopography, serving as a transitional phase between complete marsh degradation and a more permanent, uniform vegetation coverage. Biogeochemical analyses further differentiate hummocks from the hollows, with hummocks having higher concentrations of oxidized iron and total phosphorus in sediments, and lower concentrations of reduced sulfur, ammonium, and iron in porewater. This suggests plants created favorable biogeochemical conditions within the hummocks through root oxidation and other processes, similar to environments in the better-draining bank marsh despite differences in elevation and flooding (Stribling et al. 2006). The hummock and hollow topography were found to be more persistent in the interior marsh than in the exterior. The interior of the marsh deals
with higher stress conditions due to ponding and low accretion rates (Stribling et al 2007). This was consistent with our current findings, as all the hummock and hollows found were located in the interior of the marsh. In general, this topography is a biological plant driven factor caused by highly stressed conditions (Stribling 2006).

1.6. CONCLUSIONS

Sporobolus growing in higher elevations exhibited greater soil strength and higher belowground biomass than compared to those at lower elevations. In contrast, the Sporobolus marsh at lower elevation was degrading with weaker soil strength and lower biomass. Sagittaria, known for its flood tolerance, had relatively low live belowground biomass and shear strength. A hummock/hollow microtopography was found in both the degrading and stable Sporobolus marshes. However, this pattern was more pronounced in the degrading marsh. The hollows had lower shear strength and less biomass compared to the hummocks. The hummock/hollow topography, while a natural occurrence, makes Sporobolus dominated marshes more susceptible to erosion. This is a significant finding as erosion can lead to the loss of valuable marshland, which serves as a crucial habitat for a variety of flora and fauna, and also plays a vital role in maintaining the ecological balance of the area. This study not only highlights the vulnerability of Sporobolus marshes but also provides valuable insights that could be important in planning future restoration projects. By understanding the factors that contribute to the weakness and subsequent erosion of these marshes, strategies can be developed to strengthen these areas and make them more resilient. This study aligns with other studies that show Sporobolus marshes tend to be weaker under conditions of high inundation than compared to less inundated Sporobolus marshes (Hollis and Turner 2021, 2019, 2018; Snedden et al 2015, Jafari et al 2019).

High inundation conditions can lead to increased waterlogging, which in turn reduces the shear
strength of the marshes, making them more prone to erosion. This study adds to the growing body of evidence that suggests that *Sporobolus* marshes, particularly those with a hummock/hollow topography, require targeted conservation efforts to prevent further erosion and degradation. This knowledge is not only crucial for the preservation of these marshes but also for the broader goal of maintaining biodiversity and ecological balance.
CHAPTER 2. EFFECTS OF FLOODING AND NUTRIENT AVAILABILITY ON PRODUCTIVITY AND SOIL STRENGTH OF SPOROBOLUS PUMILUS AND SAGITTARIA LANCIFOLIA

2.1. INTRODUCTION

Flooding plays an important role in regulating the productivity and survival of coastal marsh plants (Mendelssohn et al. 1981, Visser and Sandy, 2009, Pezeshki 2001). While marsh plants are adapted to flooding, anaerobic conditions, and the buildup of phytotoxins associated with flooding can reduce plant productivity potentially having consequences on marsh stability (Pezeshki 2001). Plant species also differ in their flood tolerances related to species-specific abilities for anaerobic respiration and morphological adaptations that facilitate oxygen transport to the roots such as the diameter of rhizomes and aerenchyma tissue (Striker et al. 2012). A diversity of species occurs in brackish and intermediate salinity marshes that differ in their response to inundation. Forb species such as Sagittaria with large rhizomes, abundant aerenchyma tissue, and porous and adventitious roots tend to be relatively flood tolerant (Severin 1932, Nasrullah 2022). Sporobolus pumilus is an important and dominant grass species in mid-high elevation of salt marshes and in brackish marshes. Sporobolus tends to be relatively susceptible to prolonged inundation due, primarily, to small rhizome diameters and thus a lack of root volume to transport oxygen. Therefore, high inundation can cause a reduction in Sporobolus productivity, which can result in a decrease in biomass production (Gleason 1981, Snedden and Patton 2015, Gough and Grace 1998, Pezeshki 2001).

Nutrients are necessary for plant growth but increasing the availability of limiting nutrients can alter plant community composition (Pennings et al. 2002, Van der Hoek 2004, Högberg 1986), reduce species richness (Slocum and Mendelssohn 2008, Pennings et al. 2002), and favor aboveground productivity over root growth (Darby and Tuner 2008, Haase et al.)
A considerable effort has been made to understand the effects of nutrient-enrichment on salt marsh plant productivity and marsh accretion, where the findings have been inconsistent (Anisfeld and Hill 2012; Day et al. 2013; Deegan et al. 2012; Fox et al. 2012; Kearney et al. 2011; Langley et al. 2009; Morris et al. 2002; Turner et al. 2009; Valiela et al. 2023). High nutrient levels have been shown to reduce belowground biomass, thereby reducing the strength of the soil (Turner 2010, Darby and Turner 2008). Root tensile strength decreases in *Sporobolus* with an increase in nutrients such as nitrogen and phosphorus (Hollis and Turner 2019). Nutrient-loading can also lead to an increase in decomposition which in turn could create a reduction in shear strength (Turner 2011, Swarzenski 2008). Marshes subject to nutrient enrichment may experience a reduction in soil strength rendering them more vulnerable to the forces of wind, waves, and tropical cyclones (Turner et al. 2020, Turner 2011, Jafari et al. 2019).

Flooding and anaerobic conditions can reduce nutrient uptake, thereby influencing plant response to nutrient loading (Morris and Mendelssohn 2000). Flood stress can make roots more permeable to water, which can disrupt their ability to absorb water and ions (Striker et al 2012, Bailey-Serres & Colmer 2014) and reduce root biomass and thus the surface areas for ion uptake (Striker et al 2012, Alam 1999). Due to the metabolic importance of oxygen, inundated conditions can negate the impact of nutrient addition due to the inability for roots to perform regular nutrient absorption functions (Wong et al. 2015, Watson et al. 2014). A study looked at the interaction between nutrients and flooding and found that nutrient availability and flooding stress interact to influence the growth of *Taxodium distichum*. While high levels of nutrients were detrimental, moderate levels helped negate the effects of flooding stress on stem length after one year and enhanced growth after two years, except in the most flooded conditions (Nyman and Lindau 2016). Site hydrology was found to be a more influential factor than nutrient
addition in biomass growth rates (Edward 2015). When flooding persists for an extended period, anaerobic conditions can develop, leading to a decrease in photosynthesis rates. As a result of these reduced photosynthesis rates, the pattern of biomass production can change. Specifically, root growth may be impacted more significantly than shoot growth (Klundze and DeLaune 1994; Pezeshki 2001). While the effects and interactions of flooding and nutrients on marsh plant productivity have been relatively well studied, little is known about the potential feedback between belowground productivity response to inundation and nutrients on soil shear strength. In coastal wetlands, the production of rhizomes and roots as well as the accumulation of dead organic matter contribute to accretion and resilience to sea-level rise (Nyman et al. 2006; McKee et al. 2007), a potential reduction in belowground productivity could reduce the strength of the soil and increase the vulnerability to erosion.

Here, we experimentally test species-specific response to flooding and nutrient input and feedback on soil strength. Specifically, we hypothesize that belowground biomass and soil shear strength of *Sporobolus pumilus* is lower at low elevations and is similar under all elevations for *Sagittaria lancifolia*. Further, nutrient-enrichment was predicted to lower belowground biomass and soil strength particularly at higher elevations where nutrient uptake is not limited by anaerobic conditions. Soil type was also predicted to be an important factor for *Sporobolus* response to flooding and nutrients. Soils with high organic matter content can have lower shear strength due to low densities within the soil while clay soils have higher shear strength measurements due to high densities (Andersland et al. 1981, Burland 1990).
2.2. METHODS

To test the hypothesis that *Sporobolus* and *Sagittaria* differ in their response to flooding and nutrient-enrichment, we conducted a controlled greenhouse experiment. Plant material was collected from a *Sporobolus* dominated marsh in Sabine National Wildlife Refuge, Calcasieu, Louisiana in the Chenier Plain region of Louisiana where large robust stands of *Sporobolus* occur. *Sagittaria* plants were collected from an intermediate marsh in Barataria Bay. At each site 48 PVC plant plugs of each species (15.5 cm diameter and 30 cm deep) were collected and transported to the Louisiana State University greenhouses. The plugs consisted of 27 clay *Sporobolus*, 19 organic *Sporobolus* and 48 *Sagittaria*. *Sporobolus* samples were separated later on at greenhouse by either clay or organic. Core locations were chosen haphazardly to get a random sample of the area. Aboveground biomass in each plug were clipped to the soil surface prior to collection.

2.2.1. Experimental design

Ninety-six plants were placed in one of eight tanks each outfitted with a tidal control system (Aquabiotech Inc.)(Figure 13). Each tank held 519 liters and was attached to a water reserve carboy that holds 1540 liters of water. Water levels were controlled by pumps that raised and lowered the water in the tanks over a period of 12 hours (i.e., diurnal tide). Water was pumped at a rate of 760 mL/minute for each tide. A split-plot design was used for two levels of nutrients treatment and three elevations.
2.2.2. Nutrient treatment

The nutrient treatment (Ambient or Nutrient) was a whole plot factor applied to each tank. Four tanks were filled with tap water (Ambient) and four tanks had a single application of fertilizer treatment of 2mg/L of N and 0.1mg/L of P (Nutrient). The volume of water in each tank was 519 L. To achieve this ratio, 6.49 g of fertilizer with a ratio of 16-0-0 were added and 0.1153 g of fertilizer with a ratio of 0-45-0 were added to each tank.

Four of the eight tanks had a nutrient treatment using 6.49 g of Nitrate of Soda (NaNO₃) and 0.1153 g of Triple Phosphate (Ca(H₂PO₄)). This was found though the conversion of
16-0-0 (NaNO₃)

\[
\frac{2 \text{ mg N}}{1 \text{ L}} \times \frac{1 \text{ g N}}{1000 \text{ mg N}} \times \frac{100 \text{ g fert}}{16 \text{ g N}} = 0.0125 \frac{g}{L} \text{Fert} \times 519L = 6.49 \text{ g of Fert}
\]

0-45-0((Ca (H₂PO₄))

\[
\frac{0.1 \text{ mg P}}{1 \text{ L}} \times \frac{1 \text{ g P}}{1000 \text{ mg P}} \times \frac{100 \text{ g fert}}{45 \text{ g P}} = 0.0002 \frac{g}{L} \text{Fert} \times 519L = 0.1153 \text{ g of Fert}
\]

2.2.3. Elevation treatment

Three elevation treatments (low, medium, and high) were established for each species within each tank (Figure 12). Six Sporobolus and six Sagittaria plugs were placed in each tank with two of each species at each elevation treatment. The surface of low elevation plugs were 4.6 cm above low water and 33 cm below high water. Middle elevation plugs were 19.6 cm above low water and 18 cm below high water. High elevation plugs were 34.6 cm above low water and 3 cm below high water. The percentage time that the surface was flooded was approximately 90, 45, and 5\% for low, middle, and high elevations, respectively. The location of elevation and species treatments were randomized within each tank. These differences in elevation will create different percent time flooded for each group with the low elevation group having the highest percent time flooded and the high elevation group having the lowest percent time flooded.

2.2.4. Measurements

Average canopy height and stem density by species were collected for each of the 96 plugs 3 times over the 293-day study period. At the end of the study, shear vane measurements were taken using a Humboldt H-4227 Vane. This process involves the insertion of a cross-
shaped vane into the material, followed by the measurement of the necessary torque to shear the material by rotating the rod. Three shear vane measurements were collected in each plug at depths of 0, 15 and 30 cm.

Above- and belowground biomass was harvested at the end of the study. Aboveground biomass, was clipped to soil level, separated into live and dead stems by species, and dried at 60°C to a constant weight in dry pre-weighed paper bags. For belowground biomass, soil plugs were extracted from the PVC and cut into three depth segments of 0-10, 10-20, and 20-30 cm. These segments were bagged and refrigerated until processed. A 4.5 x 4.0 cm core tube was used to collect a soil sample from each depth segment for determination of ash weight (loss on ignition; LOI). The core was taken approximately 5 cm from the edge of each depth segment. The soil samples were dried to a constant weight and placed in a muffler furnace at 550°C for 8 hours. LOI was calculated by \( \frac{(\text{Final weight})-(\text{Ash weight})}{(\text{Final weight})} \). Belowground biomass was measured for each depth segment by rinsing the soil through a sieve (0.71mm) and separating the live and dead roots. The biomass was then dried at 60°C and weighed.

2.3. DATA ANALYSIS

To examine the interactive effects of species, elevation, and nutrients on plant measurements, we used a three-way split-plot analysis of variance (ANOVA) with species (including sediment type for Sporobolus samples) and elevation as sub-plot factors and nutrient treatment the whole plot factor. Response variables including canopy height, stem density, above- and belowground biomass, and soil shear strength were tested for assumptions of normality using the Shapiro Wilks test and homoscedasticity using Levine’s test. Residuals were transformed if necessary, to meet the assumptions of ANOVA. All data were analyzed using
JMP SAS pro-16 and R. For height and stem density the response variables included species (which included the sediment type in *Sporobolus*’s samples as either clay or organic), nutrient treatment (ambient or nutrient), elevation (low, mid , high), and tank number as a random effect. Interaction included species by elevation by nutrient treatment, species by elevation and species by nutrient treatment. Aboveground biomass followed a similar model as shown previously but live and dead biomass were separated and then the interactions were performed. Belowground ground also had a similar model as shown previously and the live and dead biomass was separated well. Depth was also added as a response variable in belowground biomass as a continuous repeated measure. Shear strength was tested by species, nutrient treatment, elevation, depth as a continuous repeated measure and tank as a random effect. Tukey post hoc test was performed at the end of each ANOVA except for the shear strength ANOVA. A regression analysis was conducted between biomass (live and dead) and shear strength.

2.4. RESULTS

2.4.1. Canopy height and stem density

Canopy height differed between species depending on elevation and fertilizer treatment (Elevation x Fertilizer x Species: $F_{4,87} = 3.6, P = 0.0079$; Figure 14). *Sporobolus* in organic soil responded positively to the nutrient treatment with an average height across all elevation treatments. *Sporobolus* at low elevations without a nutrient treatment in organic sediment had the highest average canopy height at 77.6 cm while *Sporobolus* at low elevation with a nutrient treatment in clay sediment had the lowest average canopy height at 18.4 cm. *Sagittaria* had a uniform canopy height across elevation and nutrient treatments.
Stem density of *Sporobolus* (organic and clay) was lower in the low elevation (3 and 4) and highest in the high elevation (8 and 12) (Species x elevation: $F_{2,85} = 7.72$, $P = 0.0008$; Figure 15). *Sporobolus* at low elevation were taller but had lower stem density than high elevation samples who had greater stem densities. Nutrients did not have an impact on stem density.

Figure 14. Canopy height of *Sporobolus* organic (A), *Sporobolus* clay (B) and *Sagittaria* (C)-dominated plugs at 3 elevations and 2 nutrient levels. Values are means ± standard error (n=3)
Aboveground biomass

The nutrient treatment did not affect aboveground biomass for either species in any elevation treatment. Aboveground biomass of *Sporobolus* was greater than *Sagittaria* across nutrient and elevation treatments (Species: $F_{2,94} = 18.53$, $P < 0.0001$). *Sagittaria* biomass was consistent at different elevations (Figure 16). There was an interaction between species and elevation treatment (Species x Elevation: $F_{2, 35} = 4.5$, $P < 0.0176$). With high *Sporobolus* clay samples having 10 g more of aboveground biomass than the low elevation counterpart. *Sagittaria* produced less aboveground biomass overall compared to *Sporobolus*, but the *Sagittaria* samples stayed consistent within their aboveground biomass and were unaffected by nutrient or elevation differences.

![Aboveground biomass of *Sporobolus* organic (A), *Sporobolus* clay (B) and *Sagittaria* (C) at three elevation treatments (Low, Mid and High). Values are means ± standard error (n = 4)](image)
2.4.3. Soil organic matter and bulk density

Percent soil organic matter (% LOI) differed between species ($F_{2,26} = 20.23$, $P < 0.0001$; Figure 17). Percent organic in *Sagittaria* was approximately 1.5 times more than *Sporobolus* in both clay and organic soil. Percent organic in *Sporobolus pumilus* in organic soil was greater ($17.2 \pm 3.2\%$ LOI) than in clay soil ($13.7 \pm 1.6 \%$LOI). Depth, elevation, and nutrient treatment did not have a significant effect on soil organic matter content.

![Figure 17. Percent loss on ignition in soil of *Sporobolus* clay plugs, *Sporobolus* organic plugs and *Sagittaria*. Values are means ± standard error ($n = 4$).](image)

2.4.4. Soil shear strength

Shear strength was significantly greater at high elevation than at low and mid elevation with *Sporobolus* in organic sediment at low elevation having the weaker shear strength (1.4 kPa).
the high elevation *Sporobolus* in clay and high elevation *Sagittaria* having the highest shear strengths (4.8 kPa and 3 kPa; Species/soil type x Elevation: \(F_{4, 217} = 5.2, P < 0.0001\); Figure 18). Shear strength also differed among elevations depending on nutrient treatment (Elevation x Nutrient: \(F_{2, 233} = 6.13, P = 0.0025\)). High elevation samples had 1.8 x stronger shear strengths when compared to the low elevation samples. *Sporobolus* in clay sediment had higher shear strength in the nutrient treatment than in the ambient conditions in the high elevation samples. Soil depth affected strength in all species (Depth x Elevation: \(F_{2, 19} = 7.68, P = 0.0007\)) with the top 0-10 cm in the high elevation treatments, having the higher shear strengths (3.6 kPa) and the low elevation treatments in the bottom 10-20 cm having the lowest shear strength (1.3 kPa).

![Soil shear strength at three depths (0,10,20cm) in plugs. On the top row without a nutrient treatment- *Sporobolus* in organic soil (A), *Sporobolus* in clay (B) and *Sagittaria* (C). With a nutrient treatment, on the bottom row is *Sporobolus* in organic soil (D), *Sporobolus* in clay soil (E) and *Sagittaria* (F). Values are means ± standard error (n = 2).](image-url)
2.4.5. Belowground Biomass

Live belowground biomass differed between species and soil types (Species/soil F\(_{2,24} = 4\), P = 0.0195; Figure 19). Sagittaria has the greatest average live belowground biomass whereas Sporobolus in organic soil had the most dead below ground biomass (Figure 19). Live and dead belowground biomass declined with depth across species and soil types (Depth: F\(_{3,5} = 30.66\), P < 0.001; F\(_{3,4} = 7.13\), P < 0.0001, respectively; Figure 20).

![Graph showing belowground biomass of Sporobolus in organic and clay soils and Sagittaria after 1 year in a greenhouse at different levels of flooding and nutrient availability. Values are means ± standard error (n=4)](image)

Figure 19. Live and dead belowground biomass of Sporobolus in organic and clay soils and Sagittaria after 1 year in a greenhouse at different levels of flooding and nutrient availability. Values are means ± standard error (n=4)
Relationship between belowground biomass and soil strength

Shear strength was positively but weakly related to live belowground biomass across species and depths ($R^2 = 0.12$, $P < 0.0006$; Figure 20).

Figure 20. Live and dead belowground biomass averaged across species and soil types at depths of 0-10, 10-20, and 20-30 cm. Values are means ± Standard error (n = 2).

2.4.6. Relationship between belowground biomass and soil strength

Shear strength was positively but weakly related to live belowground biomass across species and depths ($R^2 = 0.12$, $P < 0.0006$; Figure 20).
Figure 21. Relationship between shear strength and live belowground biomass.

2.5. DISCUSSION

Excessive flooding can lead to a reduction in biomass and growth of *Sporobolus* (Spalding and Hester 2007, Visser and Sandy 2009). Here, *Sporobolus* growing at low elevation had lower aboveground biomass and stem density than compared to the high elevation samples. *Sporobolus* at lower elevation had a high quantity of dead belowground biomass, low live belowground biomass, and weaker soil shear strength than at high elevations in ambient water conditions without nutrient-enrichment. Shear strength declines in highly flooded conditions (Tengbeh 1993). The tensile root strength of *Sporobolus* decreases up to 63% after a flooding treatment (Hollis and Turner 2019). *Sporobolus* roots can experience a decrease in root tissue density under flooded conditions (Nadioo and Mckee 1992). In the present study, the impact of flooding was influenced by substrate type. *Sporobolus* in clay sediment at low elevations had the
lowest amount of live belowground biomass when compared to higher elevation counterparts in the clay sediment. *Sporobolus* in organic sediment at low elevation had the greatest dead belowground biomass as compared to the high elevation *Sporobolus* is organic sediment. In contrast to *Sporobolus*, *Sagittaria* is relatively flood-tolerant maintaining similar rates productivity under flooded conditions (Visser and Sandy 2009, Martin and Shaffer 2005). Similarly, *Sagittaria* was not impacted by flooding in the present study.

The shear strength of *Sagittaria* soil was consistent at all elevations and weaker than *Sporobolus* at higher elevations. *Sagittaria* roots may be weaker than more fibrous root systems of *Sporobolus*, which develops a denser root system (Sasser et al. 2017). At high elevation, *Sporobolus* has higher shear strength than *Sagittaria*.

Substrate type influenced the shear strength of *Sporobolus* depending on elevation. *Sporobolus* at higher elevation with clay soils had a higher shear strength than the organic sediment samples, but at low elevations these samples experienced low shear strength indicating that the waterlogged conditions are impact soil shear strength (Hollis et al 2021). Due to differences in only physical properties at similar elevations, clay sediment samples tended to have higher shear strengths than organic sediment samples. Clay sediment has higher plasticity and hardness than compared to organic sediment (Kumari and Mohan 2021). Organic sediment is much more aerated and loose compared to clay sediment and tends to be comprised of variously decomposed material. Shear strength can be reduced by decomposition, which leads to a disintegration of organic fibers (Andersland et al. 1981).

Overall, nutrients had little impact on the below and aboveground biomass of either species, though nutrient-enriched samples in organic sediment had lower soil shear strength than
the samples in clay sediment potentially due to greater decomposed organic matter.

Decomposition can increase in organic sediment in response to a nutrient addition due to an increase in denitrification (Bulseco et al. 2019). *Sporobolus* in clay sediment did not have a decrease in shear strength within the nutrient treatment. Studies have shown an increase in biomass with the addition of nutrients for *Sporobolus* (Matzke and Elsey-Quirk 2018, Delaune et al. 2005). Stressors such as flooding can reduce and nullify the effect of nutrients on biomass growth due to the anoxic condition where the roots are unable to perform normal functions such as nutrient absorption causing none of the addition nutrients to be absorbed and thereby impact plant growth. (Watson et al. 2015, Watson et al. 2014, Wong et al. 2015). Nutrient treatment on *Sagittaria* samples does typically lead to an increase in an increase in biomass in the short term but can have negative impacts over the long term due to down-regulating belowground biomass (Graham and Mendelssohn 2016).

2.6. CONCLUSION

The greenhouse study revealed significant elevation-and substrate-dependent variation in *Sporobolus* root productivity and soil strength. Highly flooded *Sporobolus* had weaker shear strength especially in organic soil as compared to clay sediment. Nutrient addition had limited impact on the biomass of both species, suggesting that the stress induced by the elevation treatment might have overridden any potential positive effects of nutrient supplementation.

Looking ahead, these findings have significant implications for future research and environmental management. Understanding the relationships between elevation, inundation, sediment type, and nutrient availability is crucial for predicting how plant species respond to changing environmental conditions. This knowledge becomes increasingly important in the
context of climate change, where shifts in elevation and inundation rates may influence wetland ecosystems. On a broader scale, these insights contribute to our understanding of wetland resilience and adaptation, informing conservation strategies and land-use planning. As we anticipate ongoing environmental changes, incorporating such research into conservation and restoration efforts will be vital for maintaining the health and functionality of wetland ecosystems on a global scale.
## APPENDIX

Appendix Table 1.

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<th>Independent</th>
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<th>DF</th>
<th>DF error</th>
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VITA

Natalie Matheren grew up in southern Louisiana and received her bachelors in Ecology, Environmental and Evolutionary science at Southeastern Louisiana University. She began graduate school at Louisiana State University and after graduating is planning on continuing her career in coastal science in Louisiana.